

Long-Term Water Flux Changes from Converting Old-Growth Pine Forests to Hardwood Forests in Northern Wisconsin

NASA Land Surface Hydrology Program (NRA-98-OES-11)

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Project Summary

This project seeks to develop a regional understanding of land surface - atmosphere water balance changes resulting from conversion of conifer forests to hardwood forests over the last 125 years in northern Wisconsin. By utilizing an extensive database from an intensively monitored AmeriFlux (and LTER and EOS Validation) tower site in the Chequamegon National Forest, Wisconsin, airborne and spaceborne remotely sensed data, a focused set of new field measurements, and physically-based models we will synthesize a more complete, regional level understanding of the role of land use on water balance in northern Wisconsin. Specific products to be produced are seasonal and annual transpiration and soil moisture at spatial resolutions ranging from Landsat Thematic Mapper (30 m) to MODIS (1 km) for both current and reconstructed past (pre-European settlement) forest types. These products will be useful for regional modeling studies that are concerned with differentiating the relative roles of land use changes and climate change on surface and ground water budgets in the Great Lakes watersheds and the upper Mississippi River basin.

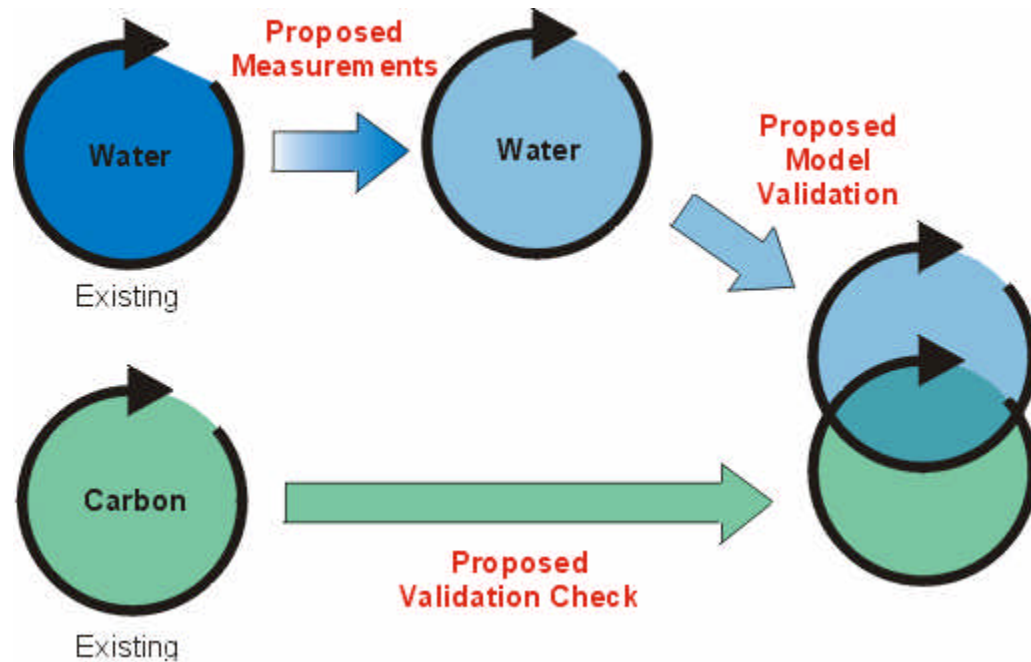
A multi-scale modeling framework will be integrated with a focused set of field measurements, working in conjunction with the *Chequamegon Ecosystem-Atmosphere Study* ([CHEAS](#), 1997), consisting of intensive field-plot measurements, an unusually tall eddy flux tower and several conventional flux towers, remotely sensed data and existing algorithms, and process-based models to better understand and quantify how complex interactions between natural landforms, vegetation cover, and land cover changes have influenced and continue to influence the pathways of water flow in northern Wisconsin. The Wisconsin site is not unrepresentative of large areas of the eastern upper Mississippi River basin and the western Great Lakes watersheds. It also differs from many other well studied sites because of the complex array of vegetation types, disturbance history, glacial landforms, and perched ground water.

Specific goals are to (1) improve knowledge of land-atmosphere water exchange in heterogeneous northern Wisconsin mixed hardwood and conifer ecosystems, (2) provide a regional understanding of water balance responses to historical land use change in the region, and (3) provide data products that can support regional hydrological and climatological modeling in the Great Lakes and the Upper Mississippi region. We will:

- Synthesize field-plot measurements, tower flux measurements, process-based models, and remotely sensed data from an existing AmeriFlux ([AmeriFlux](#), 1998) / EOS validation site, the Chequamegon Ecosystem-Atmosphere Study ([CHEAS](#), 1997);
- bridge a gap between existing leaf-scale transpiration and tower flux instrumentation with a focused set of new pre-dawn water potential and sap flux measurements;

- construct vegetation data sets for past and present forested conditions using well-established methods for the region; and
- simulate transpiration and soil water at TM and MODIS resolutions over the full study site for past and present land use using physically-based models developed for the region.

The specific scope of this project and its new contribution to the [CHEAS](#) site and regional hydrology of the area are illustrated in the following figure:



Combined water and carbon balance for model validation.

New Field Measurements

A focused set of field measurements is aimed at filling a gap in field verification of transpiration and soil water modeling being used to scale from the leaf to stand. We will add tree and stand level transpiration, and soil moisture at permanent field-plots that are representative of the range of variability in edaphic and physiological conditions. Continuous soil water content at two depths (0-30 cm, 31-60 cm) and periodic predawn water potential will be measured and compared to model predictions to determine if the model is accurately describing the hydrologic budget. We select these two characteristics because they are simple and economical, but very informative measurements that provide insight into the functioning of the model. Other more detailed measurements could be made to validate components of the hydrologic cycle, but such measurements would be extremely expensive.

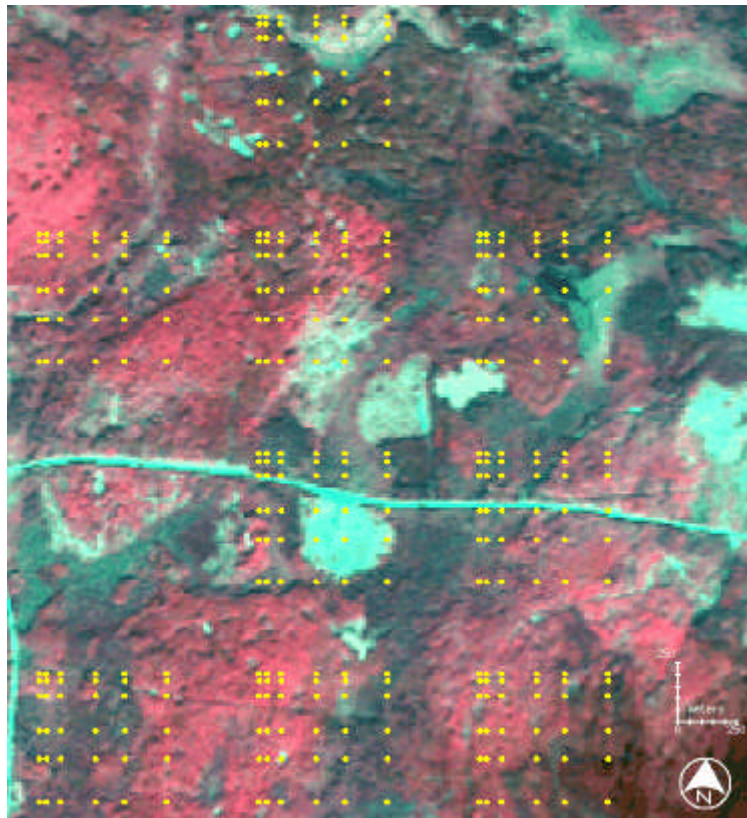
We will intensively measure soil water content and predawn water potential for three different vegetation transects, with each transect including three forests along a catena ranging from well-drained upland, mid-slope forests, and poorly-drained, lowland sites. The three upland sites will be aspen, northern hardwoods, and pine, all of which transition into lowland conifer/alder ecosystems. For each transect a data logger will be located at the middle site and cable will be run the extreme topographic positions. Campbell Scientific CS615 water probes will be installed to monitor the 0-30 cm and 31-60 cm layers at each of the nine sites. To account for spatial heterogeneity, we will install 10 neutron probe wells at each of the three sites along each transect. Soil water content will be measured every 10-12 days. On each day of soil water content measurement, pre-dawn water potential will be measured using pressure chambers (PMS Instruments, Corvallis, OR). For needle-leaf conifers individual needles will be measured. For deciduous, small twigs will be measured prior to leaf-out and then individual leaves once they have grown to full size (Williams, 1997).

A key determinant of the age-related decline in forest growth as forests age is stomatal constraint (Yoder *et al.*, 1994;

Ryan and Yoder, 1997). The increasing conservative stomatal behavior to minimize xylem cavitation of older trees, compared to young trees, has profound influence on transpiration. To incorporate this effect into the model, which would be a first for distributed hydrological models, we propose to use periodic sap flux measurements in adjacent young and old northern hardwood stands. We will use the empirical data to develop a scalar to reduce stomatal constraint as trees reach their maximum attainable height. Periodic sap flow rates will be measured using the heat flow method of measuring sap flow both within and among trees using well-known methods (Hatton *et al.*, 1995; Hatton and Vertessey, 1990), and recently applied by a graduate student advised by Gower (Williams, 1997). This will provide estimates of the variability of sap flow within and among trees, between stands across edaphic gradients, and between adjacent young and old northern hardwood stands.

Land Cover Change

Remotely sensed data will be used to produce forest cover for present-day conditions. These data include the Airborne Terrestrial Applications Sensor (ATLAS), Landsat Thematic Mapper (TM), and future NASA "EOS-era" products. We will use multi-temporal TM imagery for forest classification (Wolter *et al.*, 1995). The TM will be augmented with ATLAS 3m and 15m data to improve classification of mixed forest stands. LAI and other indices of canopy structure will be computed at a variety of resolutions, including TM (30 m), ASTER (15 m), and MODIS (1 km) data, using existing algorithms (Fassnacht *et al.*, 1997) and LAI measurements being made for EOS Validation.



ATLAS 15m data with field sampling plots shown in yellow.

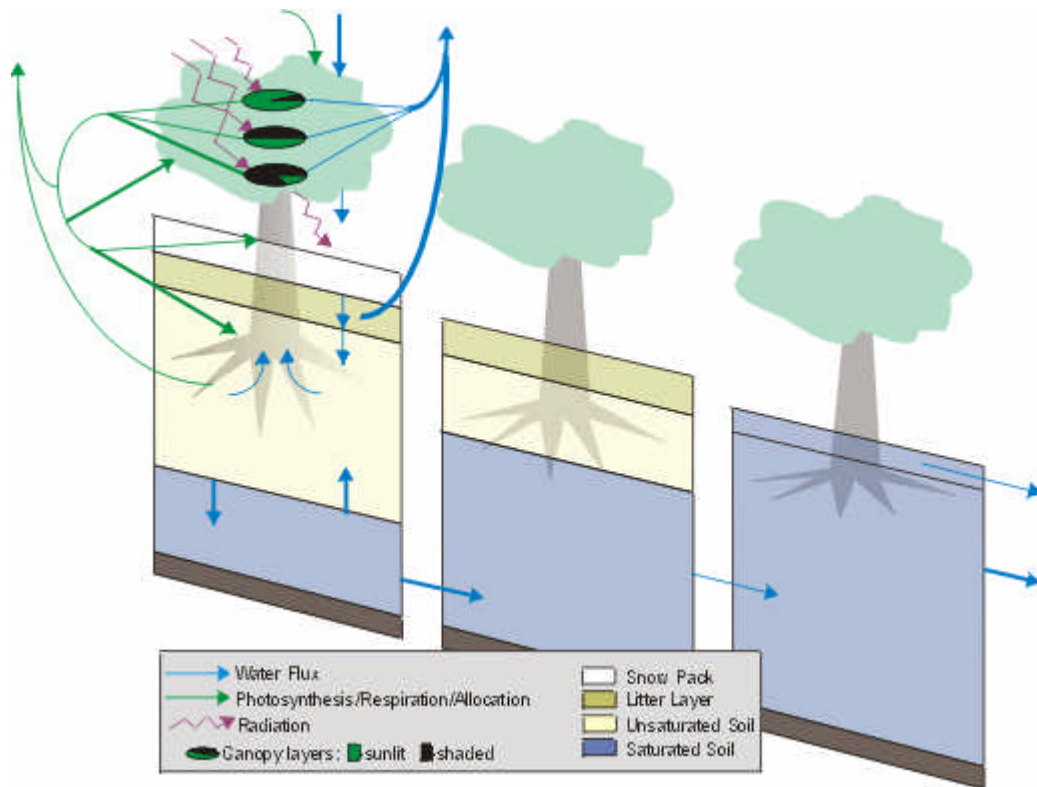
A historical forest cover map will be developed for the pre-European settlement period, using methods previously established for northern Wisconsin (White and Mladenoff, 1994). The approach relies on federal General Land Office (GLO) surveys that recorded detailed information about tree species, age, size, etc at specific locations. This information is geo-registered within a geographic information system and interpolated. LAI and other canopy parameters will be associated with the historical vegetation cover by using measurements made of a few remaining pre-European settlement old-growth conifers.

Modeling

Model simulations will be conducted using the Regional HydroEcological Simulation System, Dynamic (RHESSysD2), which is based on a previously described model (Mackay and Band, 1997) that has been modified for the northern Wisconsin site. RHESSysD2 is a spatial data processing and simulation modeling environment for representing explicitly linked water and carbon cycles in terrestrial environments at daily, annual, and multi-annual time-scales and stand-to-regional spatial scales. The model integrates distributed hydrological modeling and mechanistic biogeochemical cycling.

Digital topographic, vegetation cover type, and soils data will be used to partition the landscape around the tall tower into functional units that preserve variations in dominant drivers and ensure a parsimonious linkage between data inputs and simulated processes. A forest canopy will be superimposed on the edaphic positions and landforms. RHESSysD2 will be initialized with remotely sensed vegetation classification and LAI (Fassnacht *et al.*, 1997), but then vegetation will be dynamically grown based on environmental constraints. A hierarchical partitioning by land form, soil or edaphic characteristics, and canopy characteristics accounts for much of the variance in system drivers in the area (Fassnacht and Gower, 1997).

Soils in northern Wisconsin are relatively thin, well-drained layers overlying poorly-drained glacial ice-contact material. The contact layer varies between 50 and 70 cm below the surface layer. Preliminary analysis with SSURGO soils data, topographic data, and satellite-based leaf area index (LAI) (Fassnacht *et al.*, 1997) suggests a strong influence of lateral water flux within perched water tables formed at the contact layer. RHESSysD2 incorporates lateral subsurface flow between forest stands using topographically derived flow routing based on a compromise between lumped and grid-based routing (Tague and Band, 1997). Evapotranspiration is computed using a Penman-Monteith (Monteith, 1965) combination equation formulation.



Regional HydroEcological Simulation System (Dynamic Ver. 2)

RHESSysD2 incorporates a multi-level canopy architecture (Ellsworth and Reich, 1993; Leuning *et al.*, 1995; Williams *et al.*, 1996). Absorbed radiation, stomatal conductance, nitrogen allocation, photosynthesis, and ET are computed in parallel for each canopy layer and are aggregated to give daily stand-level totals. Stomatal conductance is regulated using a Jarvis (1976) approach. Photosynthesis is computed using the Farquhar *et al.* (1980, 1982). Annual total canopy photosynthesis less growth respiration is allocated to leaf, stem, and root compartments following Running and Gower (1991), and will be bounded by empirical data for evergreen versus deciduous forest. Relative allocation to foliar versus root compartments is determined by the most limiting of available photosynthate, available nitrogen, and moisture stress. Carbon allocated to the foliage is used to update LAI, which provides a feedback on subsequent water use. The detailed canopy model is useful at the stand level (McNaughton and Jarvis,

1991) for capturing non-linear responses when aggregating stands up to footprint of the tall tower (*e.g.*, Goulden *et al.*, 1996).

We advocate a spatial nesting approach and multiple-variable analyses to evaluate model performance. An EOS Validation project (Gower PI) will provide net primary productivity measurements needed to verify ecophysiological components of RHESSysD2. The proposed project will provide the necessary measurements and data integration to validate the hydrological components of RHESSysD2. By validating both simultaneously we provide a constraint against over-parameterizing one aspect at the expense of the other. Continuous and periodic soil moisture and pre-dawn xylem water potential measurements -- two key parameters that influence transpiration -- will be compared to model output. RHESSysD2 will be validated at (1) stand and stand transects, and (2) tall tower footprint or regional scales. This scaling-up will allow us to account for non-linearity in the relationships between topographic and soil heterogeneity, and water fluxes, which is obscured at the scale of the footprint for the tall tower. At the stand level canopy estimates of transpiration from the model for upland northern hardwoods and lowland conifer will be compared to transpiration estimates derived from eddy covariance technique (K. Davis). Specific attention will be given to seasonal pattern and annual sum. Transpiration estimates derived from the model for the region will be validated using three approaches: (1) eddy flux, (2) thermal remote sensing, and (3) comparative modeling. Modeled transpiration will be compared to transpiration estimates derived from tall tower eddy flux measurements (P. Bakwin). Again, seasonal variation and annual totals will be the focus.

ET at the regional extent will be validated using GOES thermal data and the two-source time-integrated model, TSTIM (Anderson *et al.*, 1997). The TSTIM model estimates surface fluxes by correlating the amplitude of diurnal surface temperature variations and soil moisture content. The method operates over a coarse grid, but will still provide higher resolution than is provided by the eddy correlation from the tall tower. TSTIM latent heat flux estimates and validation (J. Norman and G. Diak). The snapshots of ET rates provided by this remotely sensed data will be used to provide an additional, high temporal resolution and moderate spatial resolution check on modeled ET.

Simulated ET obtained with RHESSysD2 at the tower footprint scale will also be compared to simulations being made by S. Denning who is applying SiB2 (Sellers *et al.*, 1996). There are important differences between modeling approaches in terms of (1) scale of measurements used for parameterizing the landscape around the tall tower, (2) spatial aggregation of the major ecosystem and hydrological drivers, and (3) explicit spatial coupling between the carbon and water cycles. We will use a finer spatial resolution and aggregate to landforms rather than regular grids. This should preserve nonlinear responses of soil moisture and ET at stand, tower footprint, and coarse resolution remotely sensed imagery (*e.g.*, MODIS 1 km).

Results and Deliverables

This research is expected to provide an improved understanding of the differences in functioning of both young and old conifer and mixed hardwood systems in association with landforms and soils in the Chequamegon Forest, which lead to changes in water budgets as a result of sweeping land use change in northern Wisconsin. The spatially extant and detailed data sets proposed will be invaluable in validating physically-based models and for the extrapolation of our understanding of the role of northern Wisconsin forests on water balance. We will produce TM and MODIS scale seasonal and annual total estimates of evapotranspiration and soil moisture for present and past reconstructed forests. These products will be useful for regional modeling studies that are concerned with the deciphering the relative contributions of land use changes and climate change on water budgets for the Great Lakes watersheds and the upper Mississippi River basin. There is currently a paucity of data to support this type of modeling.

Products developed from this research will be made available to the larger scientific community through the establishment of a miniature distributed active archiving center (mini-DAAC) that will be established at the Integrated Remote Sensing Resource Center ([IRSRC](#), 1998). The IRSRC is a multi-disciplinary, multi-site large-scale computing lab for remote sensing and related geo-spatial research. It features large storage capacity (terabyte of disk space) and high speed networking, making it an ideal resource for serving large data sets to the scientific community.

In addition to the annual progress reports and executive summaries, publications in refereed journals and presentations at national scientific meetings, and a final technical report, we will provide the following unique new data sets and model results:

1. Detailed land cover database covering both present and past vegetation types for the study site and region around the Park Falls, WI AmeriFlux tower footprint;

2. daily and annual estimates of evapotranspiration for dominant vegetation \times landform position;
3. daily soil temperature and moisture data for dominant vegetation \times landform position;
4. daily and annual estimates of ET based on field measurements and process-based modeling (RHESSysD2) over the full tower footprint; and
5. regional estimates of ET and soil moisture changes resulting from changes in vegetation cover.

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